injection current. Pulsed electrical injection leads to pulsed emission from the dot, with a single photon in each pulse, provided that the pulse width is much less than the exciton lifetime. The second order correlation function recorded for the X line with a pulse width of 400 ps (Fig. 2B(i)) shows a strongly suppressed peak at zero time delay, indicating a strong suppression of the multi-photon emission pulses from the dot. This contrasts with the pair correlation recorded for the wetting layer electroluminescence (Fig. 2B(ii)).

QTuG2 **3:00 pm**

An Optically Induced and Detected Bell-Like State in a Single Quantum Dot

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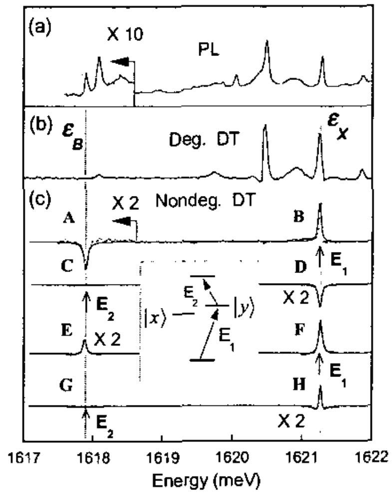
A single quantum dot (QD) exciton is considered as a basic unit capable of carrying one bit of quantum information (qubit).[1-4] Reference[5] has demonstrated exciton Rabi oscillations in single QD's that are equivalent to single-bit rotations. To realize two-bit quantum logic operations in the next step, it is essential to identify and coherently manipulate two interacting single QD excitons. Our earlier work shows that two-exciton entangled states not involving the biexciton can be optically induced.[6] This paper extends the entanglement to include the biexciton and show that all four basis states of the two-exciton system can be coherently manipulated based on a coherent nonlinear optical spectroscopy technique. The mutual coherence between the two excitons is maintained during the biexciton lifetime and surprisingly, there is no evidence of pure dephasing interactions that lead to the destruction of this exciton-exciton coherence. While the two excitons studied are confined within a single dot, the measurements demonstrate the feasibility of our approach to studies of QD structures that would be potentially scalable to larger systems.

Data were taken from GaAs interface fluctuation QD's[7] (with 0.5 μm spatial resolution) based on homodyne-detected coherent nonlinear optical response induced by two mutually coherent CW fields $E_1(\Omega_1)$ and $E_2(\Omega_2)$.[8] The response can be homodyne-detected with either E_1 or E_2. Figure 1 (a) and (b) are PL and degenerate ($\Omega_1 = \Omega_2$) coherent nonlinear spectra respectively, showing the single QD resonances. To study the biexciton, E_1 and E_2 are tuned to excite the exciton transition and exciton to biexciton transition respectively. Experimental results are shown in curves A, D, E and H of Figure 1 (c); the inset indicates the excitation scheme. The difference between the frequency of the two transitions is determined by the biexciton binding energy (3.360 ± 0.001 *meV*).

The biexciton can be excited either via a incoherent stepwise process in which the exciton state is populated first, or a coherent two-photon process using the exciton state as a virtual intermediate state. The two exciton transitions are Π_x and Π_y polarized. In our measurements, E_1 and E_2 are polarized such that only the $|y\rangle$ exciton is involved.



QTuG2 **Fig. 1.** (a) PL spectrum showing isolated resonances from single QD's. (b) Degenerate CW nonlinear optical spectrum taken from the same set of dots. (c) Nondegenerate CW DT spectra demonstrating the coupling between the resonances at ε_X and ε_B, which are identified as coming from the exciton-to-ground and biexciton-to-exciton transitions of a single QD respectively. In curve A, B, E and F (C, D, G and H), E_1 (E_2) is fixed at ε_X ($\surd_B$) and E_2 (E_1) is scanned. In curve A, B, C and D (E, F, G and H), the nonlinear optical signal is homodyne-detected with E_2 (E_1). For curves A, D, E and H, E_1 and E_2 excite the exciton and biexciton transitions respectively, as indicated in the inset. Dots are experimental data and solid lines are theoretical calculations.

By detecting E_2, both processes contribute to the signal, yielding curves A and D of Figure 1 (c), in which Ω_2 and Ω_1 are scanned respectively. The negative sign of the signal indicates that E_2 experiences induced absorption due to the presence of E_1. By detecting E_1, however, only the two-photon process contributes, yielding curves E and H. The two-photon coherence is equivalent to a coherent superposition state $\alpha|00\rangle + \beta|11\rangle$, where the $|00\rangle$ and $|11\rangle$ are the ground and the biexction state respectively. The positive and strong signal suggests that the two-photon coherence lives long enough not to diminish its contribution to the nonlinear signal. From the linewidth of curve E, the two-photon coherence dephasing time is extracted to be 22 picosecond, compared to the exciton lifetime of 13 picosecond (extracted by studying the nonlinear optical spectra of a single exciton shown in curves B and E) and biexciton lifetime of 11 picosecond. The results suggests that the exciton-exciton two-photon coherence is maintained during the exciton/biexciton lifetime.

As a result of such excitation, a superposition state involving the ground, the biexciton and the $|y\rangle$ exciton states is excited. The above discussion show that such superposition is coherent and lives until the biexciton recombines. It can not be factorized into a product state involving the two single excitons. Further experiments using strong transient excitation show that it is possible to create an equal coherent superposition of only the ground and the biexciton state,[9] reminiscent of one type of Bell state in a system consisting of two spin-$\frac{1}{2}$ particles. The measurements here show that, given our separate demonstration of Rabi oscillations on both the ground-to-exciton and exciton-to-biexction transitions, we are now in a position to demonstrate a two-bit quantum control-not gate.

This work is supported by ARO, AFOSR and ONR.

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QTuG3 **3:15 pm**

An Efficient Source of Single Photons: A Single Quantum Dot in a Micropost Microcavity

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Regulated single photons are of interest for their potential applications in quantum cryptography, quantum computation, and other areas. One of the most promising single-photon sources is a single quantum dot. We make quantum dots by strain-induced self-assembly during the molecular-beam epitaxy of InAs on GaAs. We isolate one island from the ensemble, and excite it with pulses from a mode-locked Ti:Sapphire laser. The wavelength of photons emitted by recombination in the quantum dot is uniquely determined by the number of confined carriers. It is thus possible to spectrally isolate the one-exciton emission line and obtain only one emitted photon for each laser pulse.[1,2,3]

The usefulness of this source is limited by its low efficiency. The dot radiates primarily into the semiconductor substrate, and very few of the emitted photons are captured by the collection optics. To improve on this, we place the dot inside a microscopic optical cavity. If the quantum dot is resonant with a confined cavity mode with a long photon storage time and a small mode volume, the emission rate into that mode will be significantly enhanced. Micropost microcavities are well suited for this purpose.[4,5] These cavities are made by depositing distributed-Bragg reflectors (DBR's), or GaAs/AlAs dielectric mirrors, above and below the quantum-dot layer during the MBE growth. Micron-scale posts are then etched into the sample, as shown in Fig. 1. This isolates one quantum dot from the ensemble, and also confines light in the lateral direction by total internal reflection.

We have demonstrated strong enhancement of the spontaneous emission rate for a single quantum dot coupled to a single microcavity mode.[6] The majority of the light emitted from the dot is captured by this mode. The microcavity can be designed such that confined light escapes almost entirely through the top DBR in a Gaussian-like travelling wave. It can then be efficiently collected by a lens and coupled to downstream optical components. By combining this cavity-QED effect with single-photon operation, we can build an efficient source of single photons.

We have studied the micropost microcavity modes using first-principles numerical simulation. These methods have reproduced the quality factors and lifetimes observed. We have also used these simulations to optimize the design of the microcavities. We have shown that there is the possibility of simultaneously obtaining very high quality factors and low mode volumes in this system, which should allow for the observation of novel physical effects.

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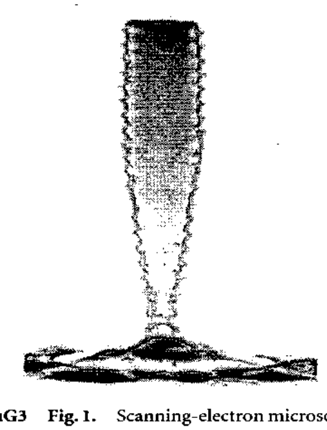

QTuG3 Fig. 1. Scanning-electron microscope image of a micropost microcavity with a top diameter of 0.6 μm.

QTuG4 3:30 pm

Polarization-Correlated Photon Pairs from a Single Quantum Dot

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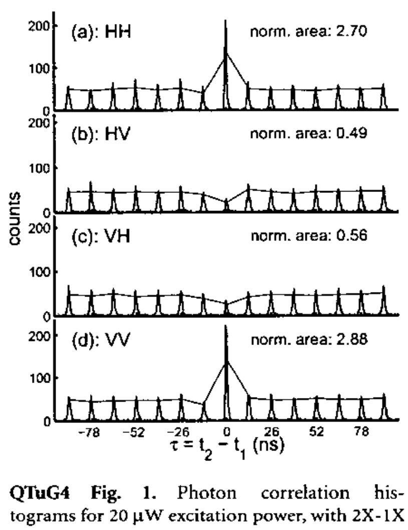
Semiconductor quantum dots are promising sources of nonclassical light because they have engineered properties and can be integrated into larger structures to make monolithic devices. Quantum dots have recently shown potential as single-photon sources, but they can also generate sequences of photons in a radiative cascade.[1,2,3,4] In such a cascade, each photon has a unique wavelength, and the photons may also have correlated, or even entangled[5] polarizations. Here, we present an experimental study of the polarization properties of photon pairs emitted through biexciton decay in a single InAs quantum dot.

A sample was fabricated containing self-assembled InAs quantum dots (11 μm^{-2}) in a GaAs matrix, etched into 0.2μm mesas. Mesas containing single dots were identified by their photoluminescence spectra. The sample, cooled to 3–5 K, was excited above the GaAs bandgap (710 nm) by horizontally polarized, 3 ps Ti-Sapphire laser pulses every 13 ns. A portion of the emission was collected, spectrally and spatially filtered, and sent to a Hanbury Brown and Twiss-type (HBT) photon correlation setup. The two arms of the HBT setup had independent measurement polarizations and wavelengths. The "start" and "stop" counters detected biexciton (2X) and single-exciton (1X) photons, respectively. For the quantum dot studied here, the 2X and 1X wavelengths were approximately 877.5 nm and 876.5 nm, respectively.



QTuG4 Fig. 1. Photon correlation histograms for 20 μW excitation power, with 2X-1X measurement polarizations (a) HH, (b) HV, (c) VH, and (d) VV.

Histograms of the delay time $\tau = t_{stop} - t_{start}$ for four polarization combinations are shown in Fig. 1. In this basis, "H" is a polarization rotated 18° from lab horizontal, and V ⊥ H. We note that the H:V intensity ratio is nearly 2:1. The area of the central peak ($\tau = 0$) is proportional to the 2X-1X coincidence rate, while the side peaks provide a normalization standard. The large central peaks for the 2X-1X polarization combinations HH and VV (a, d), compared to the small central peaks for HV and VH (b, c) demonstrate a large polarization correlation. We quantify this correlation by the function

$$\chi_{H/V} = \frac{\sqrt{C_{HH}C_{VV}} - \sqrt{C_{HV}C_{VH}}}{\sqrt{C_{HH}C_{VV}} + \sqrt{C_{HV}C_{VH}}}, \quad (1)$$

where $C_{\alpha\beta}$ is the coincidence rate for 2X and 1X measurement polarizations α and β, respectively. The measured values of χ, along with the 2X and 1X count rates, are plotted for a range of excitation powers in Fig. 2.

Negligible correlation is seen in the +45°/–45° basis ($\chi_{45°/-45°} = 0.055$). Following the procedure outlined in,[6] we measured the two-photon polarization density matrix, and found small off-diagonal elements in the H/V basis, showing no entanglement. The on-diagonal elements may be explained by a simple probabilistic model that assumes that the initial biexciton decays with equal probability through either of two single-exciton states, non-degenerate due to asymmetry.[1] Due to selection rules, one decay path emits an HH photon pair, while the other emits VV. The intensity anisotropy is best explained by different H and V collection efficiencies. This model indicates that the single-exciton polarization-flip time is at least 2.2 ns, longer than the 0.5 ns radiative lifetime.

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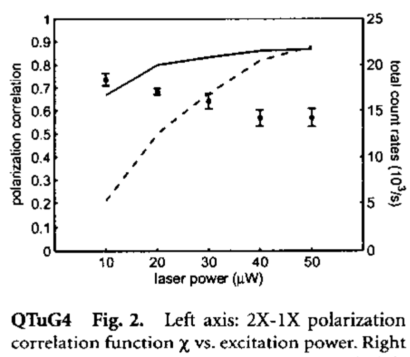

QTuG4 Fig. 2. Left axis: 2X-1X polarization correlation function χ vs. excitation power. Right axis: total (summed over polarization) 1X (solid) and 2X (dashed) count rates.